

## **Technoeconomic analysis of options for producing hydrogen from biomass**

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Hydrogen has the potential to be a clean alternative to the fossil fuels currently used in the transportation sector. This is especially true if the hydrogen is manufactured from renewable resources. The National Renewable Energy Laboratory (NREL) has examined the economic feasibility of producing hydrogen from biomass via two thermochemical processes: 1) gasification followed by reforming of the syngas, and 2) fast pyrolysis followed by reforming of the carbohydrate fraction of the bio-oil. In each process, water-gas shift is used to convert the reformed gas into hydrogen and pressure swing adsorption is used to purify the product. This study was conducted to incorporate recent experimental advances and any changes in direction from previous analyses performed by NREL. The systems examined are based on the Battelle/FERCO low pressure indirectly-heated biomass gasifier, the Institute of Gas Technology (IGT) high pressure direct-fired gasifier, and fluidized bed pyrolysis followed by coproduct separation. The pyrolysis case assumes a bio-oil feed which is shipped from remote locations to the hydrogen production plant.

The delivered cost of hydrogen, as well as the plant gate hydrogen selling price, were determined using a cash flow spreadsheet with Crystal Ball<sup>®</sup> risk assessment software. This software is able to predict the sensitivity of the hydrogen selling price to changes in various analysis parameters and determine which parameters contribute the greatest amount of uncertainty to the results. All of the parameters were varied at once, resulting in a hydrogen selling price that reflected the combined effect of the analysis assumptions.

Several cases were run for each of the biomass conversion technologies at varying plant sizes and internal rate of return (IRR) values. Three hydrogen production rates were examined for the gasification technologies: 22,737 kg/day, 75,790 kg/day, and 113,685 kg/day. For the pyrolysis case, because some of the bio-oil is used in the production of the coproduct, only the small and medium plant sizes were studied. Even with several remote pyrolysis plants, the feed required for the large plant is likely to be more than could be economically secured. The base case analysis assumes an after-tax IRR of 15%, which is a value typically required by investors. Cases were also tested at a 20% and 10% after-tax IRR and a 0% pre-tax IRR. The 20% case was chosen because these technologies are new and thus result in a higher risk. The 0% case represents the pre-tax break-even point, or the production cost of hydrogen. The 10% IRR cases are presented for illustrative purposes only, as such a low rate would probably be unacceptable to investors with multiple investment opportunities.

For any given IRR, the plant gate hydrogen selling price is lowest for the pyrolysis case (\$9-10/GJ for a 15% after-tax IRR), followed by the Battelle/FERCO gasifier plant (\$14-17/GJ for a 15% after-tax IRR), and then the IGT gasifier system (\$16-21/GJ for a 15% after-tax IRR). As the plant size increases, the hydrogen selling price decreases due to economy of scale. The delivered cost is important because even if the hydrogen is produced cheaply, the cost to store and transport the hydrogen will make a difference in determining if the hydrogen is economical. Six likely scenarios for delivered hydrogen were examined, and the cheapest storage and delivery methods were identified. For these six options, storage and delivery adds between \$1 and \$10/GJ to the plant gate cost, resulting in a delivered cost of hydrogen between \$9.9/GJ and \$32.7/GJ (using a 15% after-tax IRR) for all cases studied.

For all of the technologies examined, research should be focused on reducing the costs associated with those variables that have the largest contribution to variance. In both of the gasification options (Battelle/FERCO and IGT), the two variables having the largest effect on the uncertainty in the hydrogen selling price are the hydrogen production factor and the operating capacity factor. Combined, these two variables account for roughly 51-76% of the uncertainty in the hydrogen selling price depending on the plant size and IRR. For the pyrolysis case, the bio-oil feedstock cost, pyrolytic lignin selling price, and yield of carbohydrate from the bio-oil are the largest contributors to variance, and combine to account for 81-94% of the variability. Roughly 40-45% of the contribution comes from the bio-oil feedstock cost alone.

This study demonstrates that hydrogen can be produced economically from biomass. The pyrolysis-based technology, in particular, because it has coproduct opportunities, has the most favorable economics. However, the gasification processes also produce hydrogen for less than many other renewable technologies. An added benefit of biomass as a renewable feedstock is that it is not intermittent, but can be used to produce hydrogen when needed. Uncertainties exist, however, and must be addressed through increased research and validation projects. With scientific and engineering advancements, biomass can be viewed as a key economically viable component to a renewables-based hydrogen economy.